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Air kerma strength characterization of a GZP6 Cobalt-60 brachytherapy source

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ABSTRACT

Background: Task group number 40 (TG-40) of the American Association of Physicists in Medicine (AAPM) has recommended calibration of any brachytherapy source before its clinical use. GZP6 afterloading brachytherapy unit is a ^{60}Co high dose rate (HDR) system recently being used in some of the Iranian radiotherapy centers.

Aim: In this study air kerma strength (AKS) of ^{60}Co source number three of this unit was estimated by Monte Carlo simulation and in air measurements.

Materials and methods: Simulation was performed by employing the MCNP-4C Monte Carlo code. Self-absorption of the source core and its capsule were taken into account when calculating air kerma strength. In-air measurements were performed according to the multiple distance method; where a specially designed jig and a 0.6 cm^3 Farmer type ionization chamber were used for the measurements. Monte Carlo simulation, in air measurement and GZP6 treatment planning results were compared for primary air kerma strength (as for November 8th 2005).

Results: Monte Carlo calculated and in air measured air kerma strength were respectively equal to 17240.01 μGym^2 h^{-1} and 16991.83 μGym^2 h^{-1}. The value provided by the GZP6 treatment planning system (TPS) was "15355 μGym^2 h^{-1}".

Conclusion: The calculated and measured AKS values are in good agreement. Calculated-TPS and measured-TPS AKS values are also in agreement within the uncertainties related to our calculation, measurements and those certified by the GZP6 manufacturer. Considering the uncertainties, the TPS value for AKS is validated by our calculations and measurements, however, it is incorporated with a large uncertainty.

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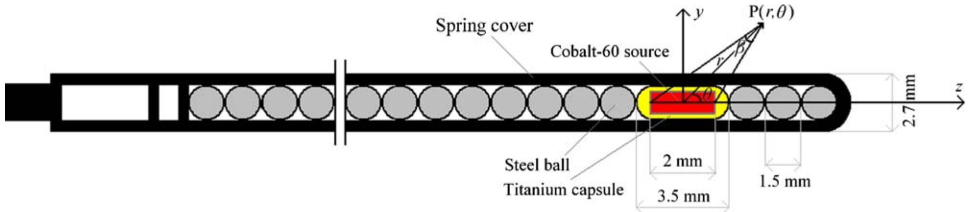

Fig. 1 – A schematic structure of the GZP6 source braid number three. The source braid consists of one active Cobalt-60 pellet and nonactive steel balls.

1. Introduction

The task group 40 (TG-40) of the American Association of Physicists in Medicine (AAPM) has recommended that every brachytherapy source must be calibrated before its clinical use.[1] The recommended quantity for calibration is air kerma strength (AKS).[2] Air kerma strength is defined as the product of air kerma rate $\dot{K}_\delta(d)$, in the free space, at the reference transverse distance from the source center multiplied by the square of this distance.[3] Although manufacturers provide AKS of the source, in some cases large uncertainties are associated with their stated values. Since the uncertainty may be as high as ±10%, it is necessary to calibrate the sources before its clinical use by the end user to verify the manufacturer's stated values.[1,2]

The GZP6 brachytherapy system is manufactured by the Nuclear Power Institute of China (NPIC).[4] It is a HDR afterloading unit having six ^{60}Co sources braids designed for treatment of rectum, cervix, nasopharynx and esophagus cancers.[5] Several studies have focused on determination of air kerma strength of ^{125}I, ^{192}Ir and ^{169}Yb brachytherapy sources being used clinically.[6–10] Mesbahi et al. have verified the ^{60}Co source numbers 1, 2 and 5 of the GZP6 unit in terms of air kerma rate.[11] However, to our knowledge, AKS of source number 3 of GZP6 had not been verified before this work was commenced. In this study, air kerma strength of the GZP6 source number 3 was estimated by Monte Carlo simulations and in-air measurements. Calculated and measured, AKS values are compared with the certified value given by the manufacturer of the source which is stated in the GZP6 treatment planning system (TPS).

2. Materials and methods

2.1. *Radioactive source structure*

The GZP6 brachytherapy afterloader is a HDR unit consisting of six braids of sources being used in the intracavitary and intraluminal cancer treatments. Each source braid has 1, 2, 3 or 4 active pellets and a number of steel balls as spacers. This study is focused on the source number three of the unit. This source is a braid having one active pellet and several steel balls. A schematic structure of the GZP6 source braid number three is illustrated in Fig. 1.

The active pellet is a cylindrical Nickel-plating Cobalt-60 source 1 mm in diameter and 2 mm in length. The source is encapsulated in titanium. The steel balls have a diameter of 1.5 mm. The active and non-active pellets are contained in a spring cover.

2.2. *Air kerma strength*

The TG-43U1 recommends to specify brachytherapy source strength in terms of "air kerma strength". According to the TG-43U1 report, air kerma strength, S_k, is defined as the product of air kerma rate $\dot{K}_\delta(d)$ in vacuo, at a transverse distance of d from the source center multiplied by the square of this distance (d^2):

$$S_k = \dot{K}_\delta(d)d^2 \tag{1}$$

The notation δ refers to the fact that only the photons with energy greater than δ are accounted for the air kerma strength

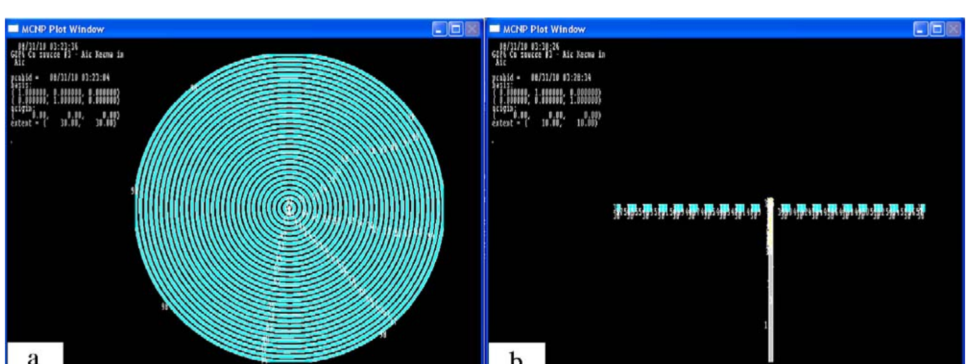

Fig. 2 – A top view (a) and lateral view (b) of the source and scoring rings plotted by the MCNP Monte Carlo code. The cylindrical rings were used to score air kerma at different distances from the source.

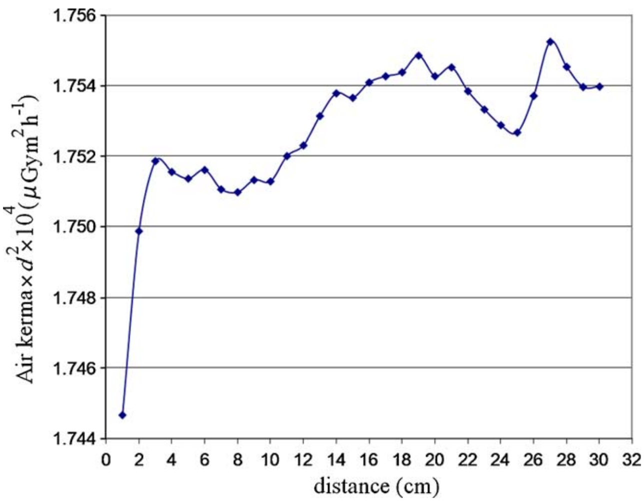

Fig. 3 – Plot of the air kerma rate × d^2 versus distance d from the source center, as obtained from MCNP simulations.

calculations. These photons may be contaminant photons, characteristic X-rays originating from the source capsule, etc., which may increase air kerma strength without having significant contribution in the dose to tissues. Air kerma strength has the unit of U, where 1 U = 1 μGym^2 h^{-1}.

The distance d should be large enough compared with the radioactive distribution length of source so that the S_k is independent of distance d. The notation "in vacuo" refers to the condition in which photon attenuation in air and scattering from different components of the measurement room are corrected for.[3]

2.3. *Monte Carlo simulations*

The MCNP 4C Monte Carlo code[12] was employed for simulations. The source braid was simulated in vacuum. Air kerma was scored by air filled cylindrical rings in the 1–30 cm transverse distance from the source center, in 1 cm increments. The cylindrical rings were 0.5 cm in thickness and 0.5 cm in length. A top view and lateral view of the source and scoring rings plotted by the MCNP code is illustrated in Fig. 2.

The F6 tally was used to score air kerma in terms of MeV/g per photon in the ring cells. The cutoff energy was defined as 5 and 10 keV for photons and electrons respectively. The energy cutoff was defined to exclude contribution of low energy particles from the total air kerma. Then the air kerma rate was plotted versus distance (Fig. 3) and the average value in the plateau region of the curve was taken as the air kerma rate.

Self-absorption of the source core and capsule was estimated through another independent simulation. In the new simulation, the same geometry for source core, capsule, etc. were introduced; while the material for source braid components was replaced by air. This geometry is commonly referred to the bare source geometry. Two 1.33 and 1.17 MeV gamma photons, emitted from Cobalt-60, were still assumed to originate from the source core (air). The air kerma values in the cylindrical cells were scored as explained earlier. The statistical error for a total number of 2×10^7 primary photon histories was 0.04% for both simulations. The self-absorption factor was defined as the ratio of new air kerma to the previous air kerma.

Finally, air kerma strength was calculated by normalization of averaged air kerma to the reference distance of 1 m multiplied by source activity, the self-absorption factor and other appropriate conversion factors. The primary activity, the activity as for the date of source production (November 8th 2005), was used in the calculation so that the primary value for air kerma strength could be obtained.

2.4. *In-air measurement of air kerma rate*

Air kerma measurements were performed according to the recommendations made by the TECDOC-1274 technical document of the International Atomic Energy Agency (IAEA).[2] According to this report, the reference air kerma rate K_R can be determined by using the following equation:

$$K_R = N_K \cdot \left(\frac{M_u}{t}\right) \cdot k_{air} \cdot k_{scatt} \cdot k_n \cdot \left(\frac{d}{d_{ref}}\right)^2 \tag{2}$$

where N_k is the air kerma calibration factor for an ionization chamber in the calibration photon energy; M_u is the chamber's reading during time t, corrected for ambient temperature and pressure, and other factors affecting the chamber's reading; k_{air} is the correction factor for attenuation of photons by air between the source and the chamber; k_{scatt} is the correction factor for photons scattered by the components of a measurement room; k_n is the non-uniformity correction factor to account for non-uniform fluence of electrons in the air cavity; d is the measurement distance, and d_{ref} is the reference distance from the source.

The scattering correction factor, k_{scatt}, is a correction factor for the scatter components in measurement of air kerma strength. To calculate this factor, we followed the multiple distance method.[2] According to this method, the distance of reading is expressed as:

$$d' = d + c \tag{3}$$

where d' is the source to chamber distance accounting for the offset c in the distance, d is the apparent source to chamber distance and c is the offset in the distance d. The total air kerma rate consists of two components: scatter and primary. Thus, the primary component can be determined by:

$$K_P(d') = K(d') - K_s \tag{4}$$

Combining Eqs. (3) and (4) results in Eq. (5):

$$K_P(d') = \frac{(K(d') - K_s)(d + c)^2}{(d')^2} \tag{5}$$

There are three unknowns in this equation: $K_P(d)$, K_s and c. By taking the measurements in multiple distances (at least three distances) the unknowns can be determined. In this study the measurements were carried out in six different distances for the redundancy purpose. The scatter component

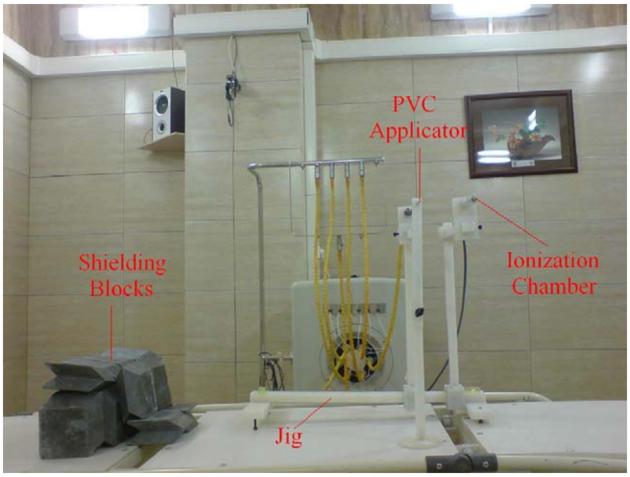

Fig. 4 – In-air measurement set-up for air kerma rate, including the jig, ionization chamber and source applicator.

known, the scatter correction factor was then calculated:

$$k_{\text{scatt}} = \frac{1 - K_s}{K(d')} \tag{6}$$

The non-uniformity correction factor is calculated from the isotropic theory of Kondo and Randolph[13] and the anisotropic theory of Bielajew[14] from the related factors. The value of nonuniformity factors of the Farmer chamber and the measurement distances were adapted from Table IX of IAEA report.[2] According to this Table for measurement distances of 10.0–20.0 cm, non-uniformity factor has a range of 1.009–1.004 depending on the measurement distance. A k_{air} factor of 1.000 was applied since this value is used for ^{60}Co sources. The source transit effects were ignored, since the readings were performed after complete loading of the source from the afterloader and were stopped before returning of the source to afterloader's case. A special thin PVC applicator was designed and the source was loaded in a PVC applicator during the measurements.

Since the sources 3 and 4 of the GZP6 afterloader are loaded simultaneously, the source 4 was loaded in a shielded case constructed from 5 cm thick lead blocks when the measurements were performed on the channel 3. Before taking any measurement, radiation leakage from the case was measured by the ionization chamber for the maximum time interval defined for the experiments, in a situation that both channel 3 and 4 were in the case and their sources were loaded. Following the above configuration, zero readings were obtained in the measurements of leakage radiation from the shielding case.

A special jig was designed for adjustment of the distance between the source and ionization chamber. The measurements were performed in the transverse distances of 10–20 cm between the source and chamber center, with 2 cm increments. The measurement set-up including the jig, ionization chamber and applicator are illustrated in Fig. 4. During the measurements the ionization chamber was positioned at a fixed point and the distance was changed by moving the applicator. A minimum distance of 1.1 m was maintained between the ionization chamber and the nearest scattering barrier (the afterloader's case) in the room.

Air kerma measurements were performed in air by a 0.6 cm^3 Farmer type ionization chamber (NE 2581, #1106) with a 0.551 g/cm^3 build up cap and an electrometer (NE Technology, 2570/1). The chamber was calibrated by the SSDL laboratory of Atomic Energy Organization of Iran (AEOI) in terms of air kerma in a standard field of a teletherapy Cobalt-60 unit.

The initial value of measured air kerma strength was determined by taking into account the date of measurement and the radioactive disintegration effect.

3. Results

In this study average air kerma in the 20–30 cm distance from the source was used to calculate the source's air kerma rate at the reference point of 1 m. However, selfabsorption in the source could not affect the air kerma strength's value considerably. The resulted air kerma strength was estimated to be 17240.01 μGym^2 h^{-1} from our Monte Carlo simulation for the GZP6 source number three.

The value for the offset c was estimated to be $\pm$1.2 mm for our in-air measurements. The value of 0.95 was obtained for the scatter correction factor. Finally the measured air kerma strength was estimated as 16991.83 μGym^2 h^{-1}. The GZP6 treatment planning system has provided the value of "15355 μGym^2 h^{-1}" for air kerma strength of this source. It should be mentioned that the AKS values stated here are referred to the date of production of the source.

4. Discussion and conclusion

In the current investigation we have estimated air kerma strength for the GZP6 number three ^{60}Co source through Monte Carlo simulations and in-air measurements. The obtained results were compared with the air kerma strength value presented by the GZP6 treatment planning system for the source. The difference between Monte Carlo calculated and measured AKS is equal to 1.44%. The difference for the calculated-treatment planning system and measured-treatment planning system values of air kerma strength for the source is equal to 10.93 and 9.63%, respectively. It is obvious that the calculated and measured AKS values are in good agreement. However, the differences between calculated-TPS and measured-TPS figures are bigger. The GZP6 manufacturer has reported a $\pm$10% uncertainty for AKS and the source's activity. Since we have used the manufacturer presented activity in our calculations, there is a minimum $\pm$10% uncertainty in our Monte Carlo calculations. Considering the percentage of uncertainties, the GZP6 TPS value for air kerma strength is in agreement with our calculated and measured values. However, it is obvious that GZP6 treatment planning system presents a large uncertainty in terms of the air kerma strength value.

Our results also have shown that the positional error may be reduced if the experimental jig is made of a more rigid material like Perspex.

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